The Optical-Infrared Extinction Curve and its Variation in the Milky Way

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Abstract

The dust extinction curve is a critical component of many observational programs and an important diagnostic of the physics of the interstellar medium. Here we present new measurements of the dust extinction curve and its variation towards tens of thousands of stars, a hundred-fold larger sample than in existing detailed studies. We use data from the APOGEE spectroscopic survey in combination with ten-band photometry from Pan-STARRS1, 2MASS, and WISE. We find that the extinction curve in the optical through infrared is well characterized by a one-parameter family of curves described by $R(V)$. The extinction curve is more uniform than suggested in past works, with $\sigma(R(V)) = 0.18$, and with less than one percent of sight lines having $R(V) > 4$. Our data and analysis have revealed two new aspects of Galactic extinction: first, we find significant, wide-area variations in $R(V)$ throughout the Galactic plane. These variations are on scales much larger than individual molecular clouds, indicating that $R(V)$ variations must trace much more than just grain growth in dense molecular environments. Indeed, we find no correlation between $R(V)$ and dust column density up to $E(B-V) \approx 2$. Second, we discover a strong relationship between $R(V)$ and the far-infrared dust emissivity.

Introduction

- The extinction curve is a basic component of observational programs.
  - extinction correction
  - survey selection function
- The shape of the extinction curve is an important diagnostic of dust physics.
  - usually parameterized by $R(V) = A(V)/E(B-V)$, roughly, steepness in optical
  - grain conglomeration → bigger grains
  - bigger grains → higher $R(V)$
- The best existing extinction curve atlases rely on hundreds of bright OB stars.
- APOGEE spectroscopy plus PS1, 2MASS, and WISE photometry enable us to study tens of thousands of stars.
- Dense sampling of wide areas in the Galactic plane enable *maps* of $R(V)$, rather than just sparse samples.
- The morphology of the maps and correlation with other interstellar medium tracers should enable new constraints on dust physics.

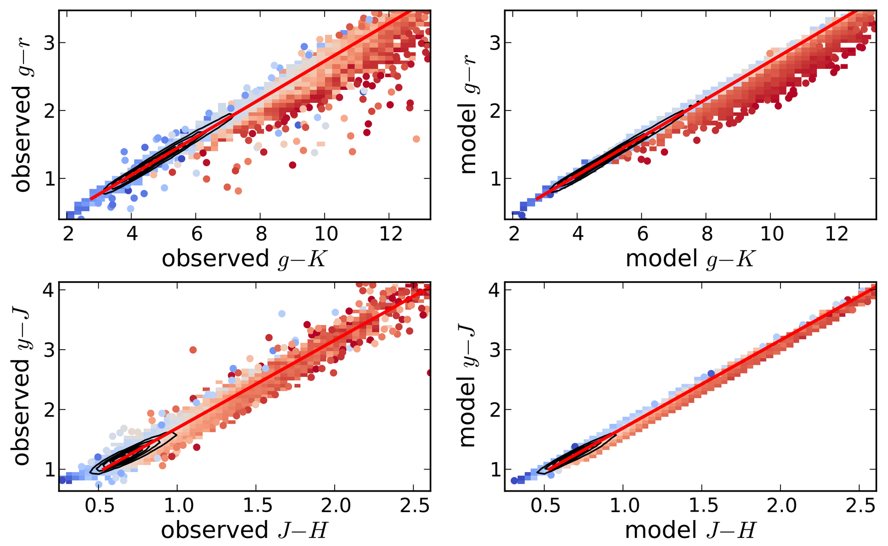
Method

We model the observed colors as the sum of the intrinsic colors (as determined from APOGEE temperatures and metallicities) and reddening.
The model is given by:

$$\vec{m}^m = \vec{f}(T, [\mathrm{Fe/H}]) + \mu + \vec{R} \times E$$

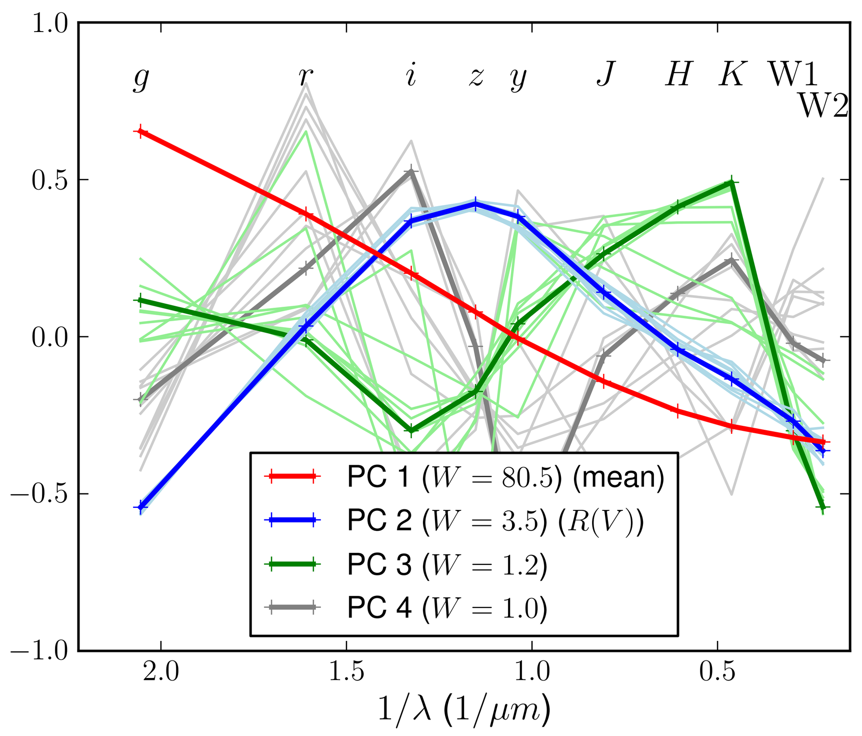
- $\vec{m}^m$ model magnitudes
- $\vec{f}$ intrinsic colors
- T temperature
- $[\mathrm{Fe/H}]$ metallicity
- μ distance modulus
- $\vec{R}$ reddening vector
- E extinction

- ~ 74000 parameters
- Excellent fit!

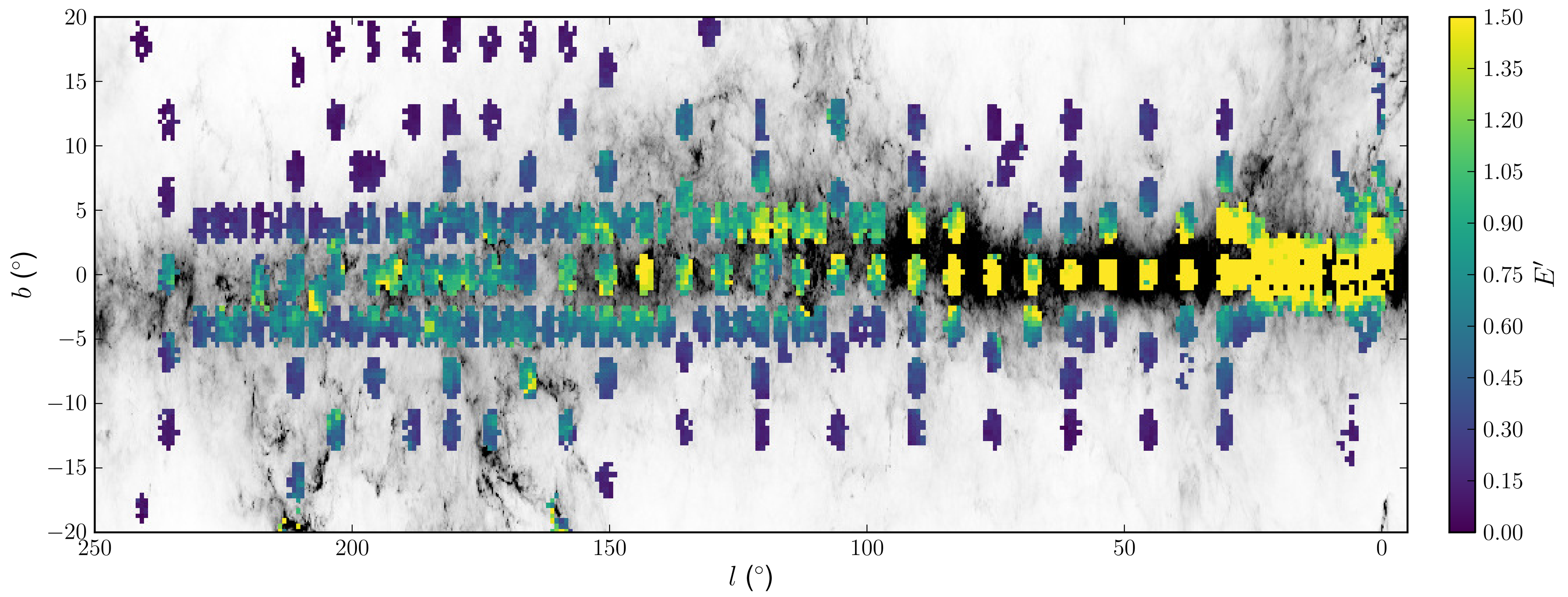


Variation in the Extinction Curve

- The initial fit gives the intrinsic colors of stars.
- The reddenings are given by the observed minus the intrinsic colors.
- We study variation in reddening through the dimensionality of the space of reddenings.
- PCA results:
  - 2 components: extinction and shape
  - other components consistent with noise ($W \sim 1$)
  - shape parameter acts to flatten extinction curve in optical: $R(V)$!



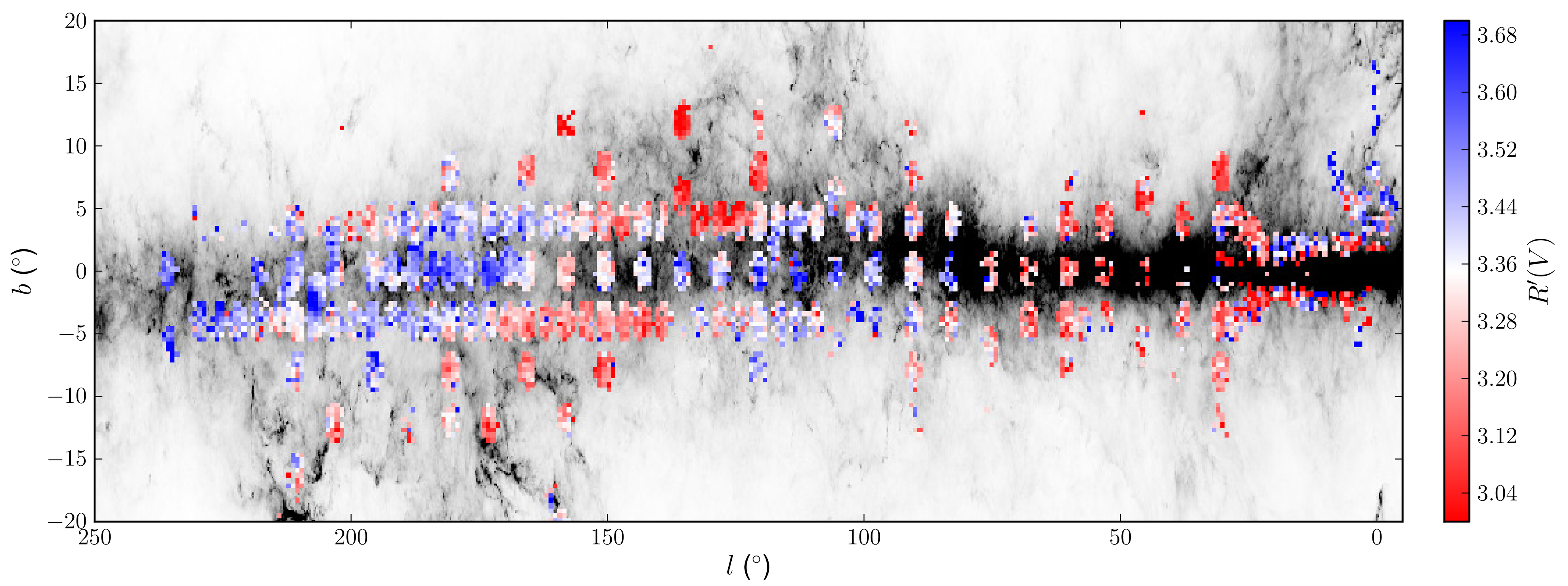
$E(B-V)$ map



We have mapped $E(B-V)$ using APOGEE throughout much of the Galactic plane.

- Wide range of ISM environments sampled
- Many highly reddened sight lines ($E(B-V) > 1.5$)

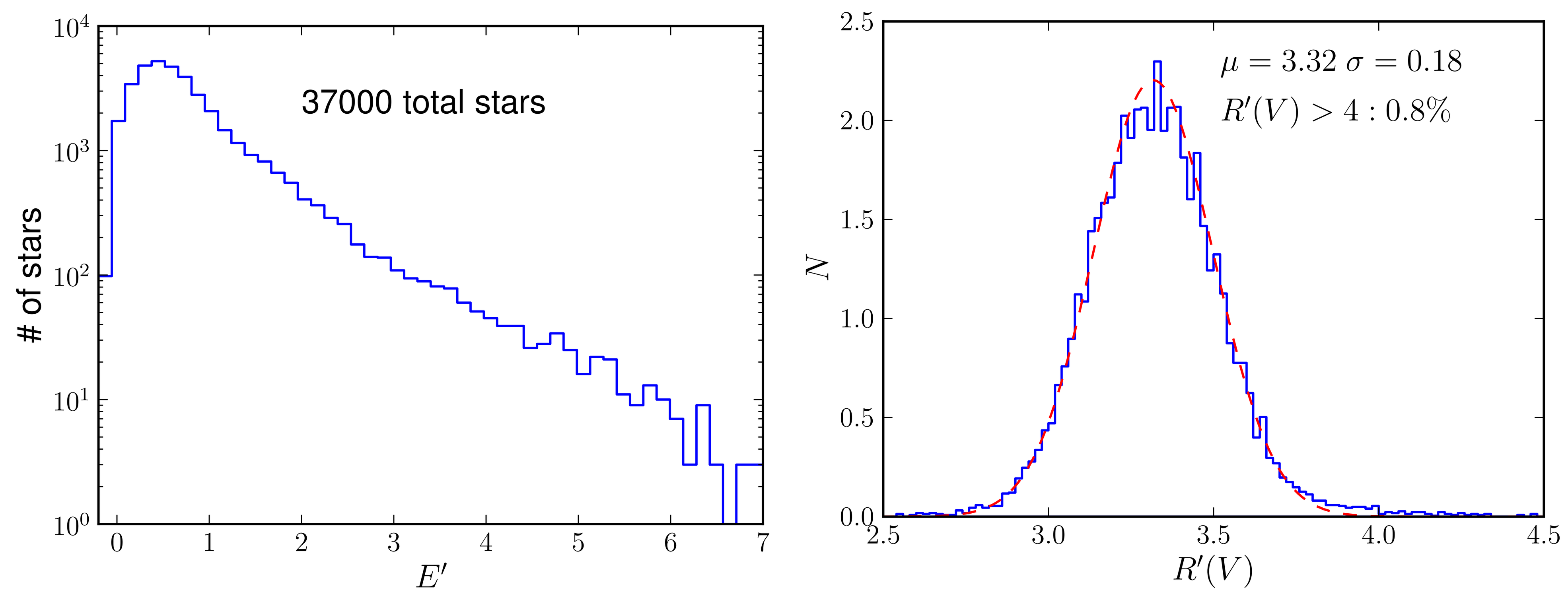
$R(V)$ map



We can likewise map $R(V)$ throughout the Galactic plane.

- First *maps* of $R(V)$ in the plane!
- Structures on very large scales
- Extended low $R(V)$ region extending from Taurus and California into Cepheus and Orion
- Features much larger than individual molecular cloud scales
  - Challenge to standard dust paradigm?
  - What physics generates $R(V)$ variations on these scales?
  - Local bubble? Gould's belt? …

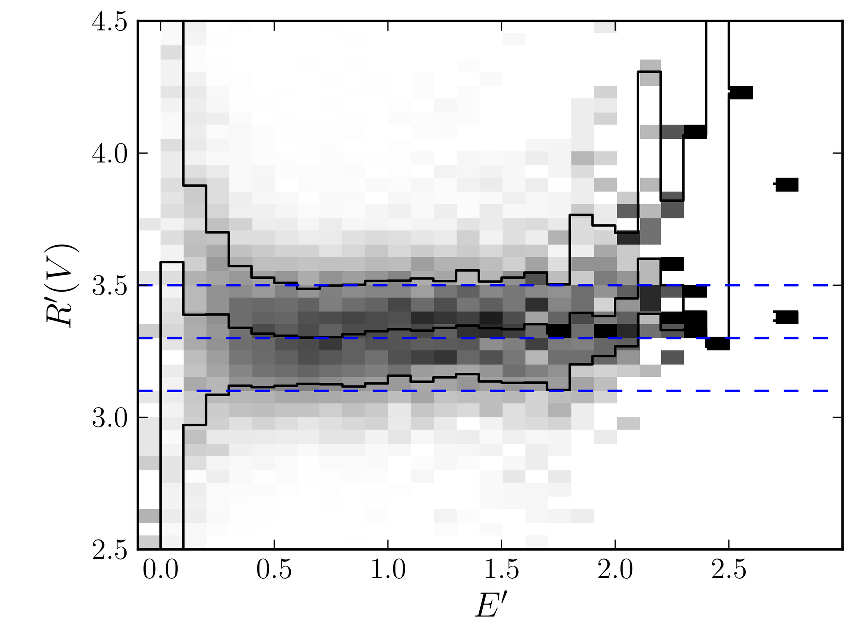
$E(B-V)$ and $R(V)$ distribution



- Tens of thousands of stars
- Typical $E(B-V) \sim 0.65$, tail to very large reddenings
- Tight distribution of $R(V)$, $\sigma \sim 0.18$
- Less than 1% of sight lines have $R(V) > 4$

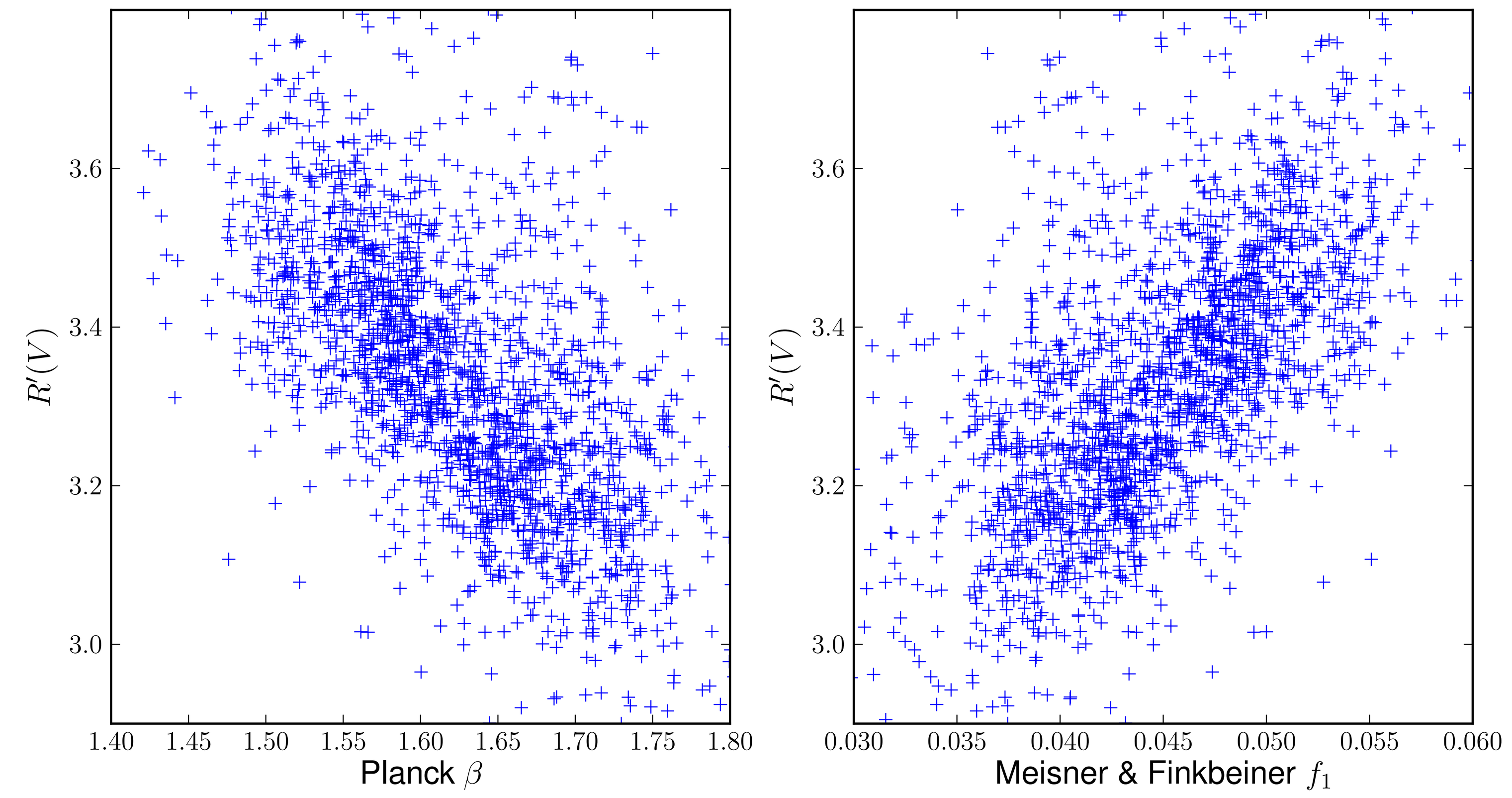
$R(V)$ versus $E(B-V)$

- Basic paradigm: $R(V)$ increases in dense regions
  - Growth of ice mantles at $E(B-V) \approx 1$
  - Grain conglomeration
- Test: does $R(V)$ systematically increase with $E(B-V)$?
- No trend in our data.
- Caveat: high $E(B-V)$ means either dense clouds or long line of sight through clouds.
- APOGEE-2 Reddening Survey will target the densest regions in nearby molecular clouds.



FIR dust emissivity versus $R(V)$

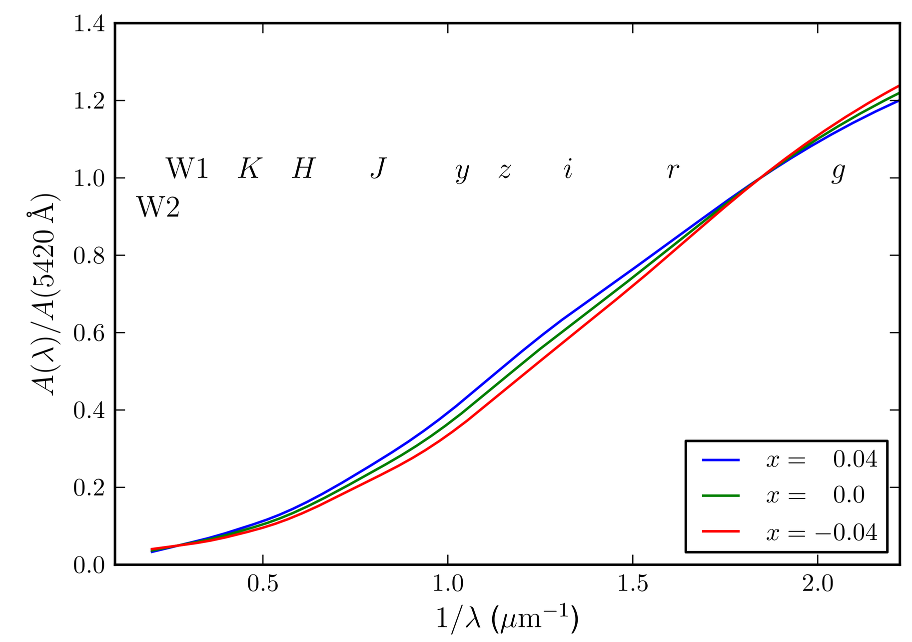
- Like the extinction curve, the dust far-infrared SED is also significantly variable.
  - Parameterized by emissivity spectral index β or in a two-component model by f_1
- Do $R(V)$ variations correlate with SED variations?



- Emphatically yes!
- Steeper extinction curves ↔ steeper FIR emissivities
- Statistically completely independent
- New constraint on models of dust physics.

New Extinction Curve

- We make new measurements of reddening at high columns throughout the Galactic plane.
- We find discrepancies with existing curves: a new extinction curve is needed.
- The right panel shows three extinction curves from our new family of curves.
- The gray component is unconstrained, and fixed using Indebetouw et al. (2005).



Conclusion

- Reddening and $R(V)$ measurements over much of the plane
- New single-parameter optical-infrared extinction curve
- Remarkably uniform: $\sigma(R(V)) = 0.18$, less than 1% of our stars have $R(V) > 4$
- Variations in $R(V)$ are coherent on large scales, encompassing several individual molecular clouds.
- We observe no correlation between column density and $R(V)$.
- We discover a strong correlation between $R(V)$ and the far-infrared dust SED.

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